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# ON ECCENTRIC SEISMIC POUNDING OF SYMMETRIC BUILDINGS

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## SUMMARY

Results of a parameter study on eccentric pounding of two symmetric single storey systems under seismic excitation are presented. Linear behaviour is assumed, and pounding effect is considered using the restitution coefficient approach. The effect of impact eccentricity is studied on two sets of symmetric models symmetrically and asymmetrically aligned with respect to each other for several gap widths, period dependent gaps and three values of the torsional-to-lateral frequency ratio. Two time histories are used for input.

On the whole it was found that impact eccentricity amplifies the response relative to symmetric impact but the effect is not proportional to first impact eccentricity. Also, increasing gap width is likely to be effective when the separation is sufficiently wide practically to eliminate contact. Larger torsional rigidity tends to lower response amplification. SRSS code-type gaps appear to be adequate, or even excessive, when the design spectrum is compatible with the expected earthquake record at the site.

KEY WORDS: earthquake engineering; impact; pounding; asymmetric structures; adjacent buildings

## INTRODUCTION

Studies of past earthquakes have shown that pounding between adjacent buildings has led in many cases to severe damage[1–3]. To eliminate pounding, seismic codes prescribe minimum gap widths. Usually the recommended gap is an estimate of the probable sum of the absolute displacements of the two adjacent buildings. However, since codes require relatively wide gaps, enforcement is problematic due to detailing difficulties and the high cost of land. Moreover, it is very difficult to ensure that gaps are always kept free of debris, and instances where wooden formwork remained in gaps and thus reduced the gap widths were reported following the Loma Prieta earthquake.[3]

Earlier studies on the effect of pounding on structural response[4–13] have shown that when floors of two buildings collide the response of the building with the smaller mass (for equal stiffnesses), and to a lesser extent that of the more rigid one (for equal masses) is amplified, depending on their period and mass or rigidity ratios. Unequal height can create problems to the lower building if it is stiffer, and to large interstorey shear forces in the taller building. It has also been argued that since pounding effects diminish with increasing gap width, any separation provided by the code should be beneficial, even when it does not entirely eliminate pounding.

Most of these studies assume two-dimensional behaviour, i.e. the colliding buildings are symmetric about the direction of motion, so that only in-plane pounding is considered. The model of Kasai *et al.*[4,5] does consider eccentric impact and thus torsion, but compatibility during impact—i.e. no overlap of the two buildings—is apparently enforced only at the point of assumed contact, whereas floor rotation (about the vertical axis) can lead to pounding at some other point along the interface of the two floor slabs—usually the corners.

However, even when the adjacent buildings are nominally symmetric and the vertical plane passing through the axes of rigidity of the two buildings is parallel to the direction of excitation [Figure 1(a)] the impact between them is not likely to be symmetric. This is because the gap between the two colliding floor slabs is seldom of exact constant width throughout and, as noted, hard debris, either left over after

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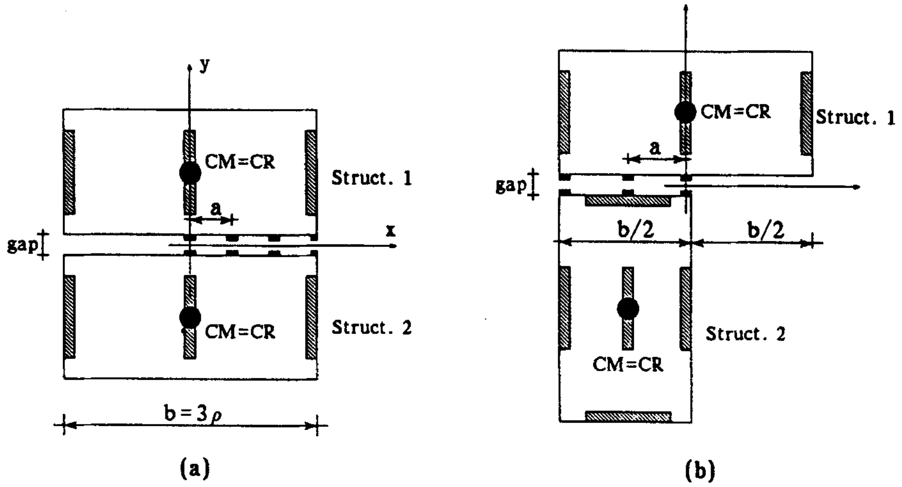


Figure 1. Model geometries: (a) Symmetrically aligned floor slabs. (b) Asymmetrically aligned floor slabs

construction or accumulated since, can close or narrow the gap at an arbitrary point. Indeed, experimental studies carried out by the authors[12] have shown that after impact the motions of two colliding identical symmetric plates are no longer truly translational. Moreover, the vertical plane through the axes of rigidity of the two buildings is, more often than not, at an angle to the direction of excitation [Figure 1(b)] resulting in an eccentric impact. It is thus evident that torsion is practically always present after impact, even in symmetric buildings, and therefore should be considered in design.

The purpose of this paper is to present some results of a parametric study on the effects of eccentric impact on the response of symmetric single storey buildings with vertically aligned roof slabs. Modelling the floor behaviour during impact is more involved, and may not be necessary for evaluating the response of the supporting structural system. Therefore, the classical restitution coefficient approach to impact (e.g. Reference 14), which obviates this problem, was adopted. With this approach an infinitesimal displacement during an infinitesimal interval of impact is assumed. It also requires a quantitative estimate of the restitution coefficient.

## THE MODELS AND PARAMETRIC STUDY

Eccentric pounding of two adjacent single storey or, as a first approximation, of two multistorey building models of equal height, shown in Figures 1(a) and (b), is investigated numerically in this study. The first model represents the case of two symmetrically aligned symmetric rectangular buildings of similar plan dimensions [Figure 1(a)]. The second model represents two different symmetric buildings, with their fronts aligned along the same boundary [Figure 1(b)]. Equal mass and stiffness properties were assumed for the two buildings, and $\Omega = \Omega_1 = \Omega_2$ ($\Omega$ = torsional to lateral frequency ratio). Even for these simple models the number of geometric and structural parameters is very large, and the slab aspect ratios chosen for Figure 1 are necessarily arbitrary. To study the effect of torsional stiffness three values of $\Omega$ were used: $\Omega = 0{\cdot}8$, $1{\cdot}0$ and $1{\cdot}25$. Different frequency ratios are obtained by choosing appropriate ratios for the stiffness of the central element in the structure to that of the edge elements. Note that structures with $\Omega = 0{\cdot}8$ are considered to be torsionally flexible, while $\Omega = 1{\cdot}25$ represents the lower bound of torsionally rigid structures. Typical $\Omega$ values in buildings are close to $1{\cdot}0$.

Asymmetric impact was induced by either assuming a small local protrusion (say 1·0 mm) from the floor edge, or by simply specifying contact at a given point. This point was located at $a = 0, 0{\cdot}5\rho, 1{\cdot}0\rho$ and $1{\cdot}5\rho$ from the axis of symmetry ($\rho$ = mass radius of gyration taken herein as $\frac{1}{3}$ of the floor width). Evidently $a = 0$ represents symmetric impact for the model in Figure 1(a).

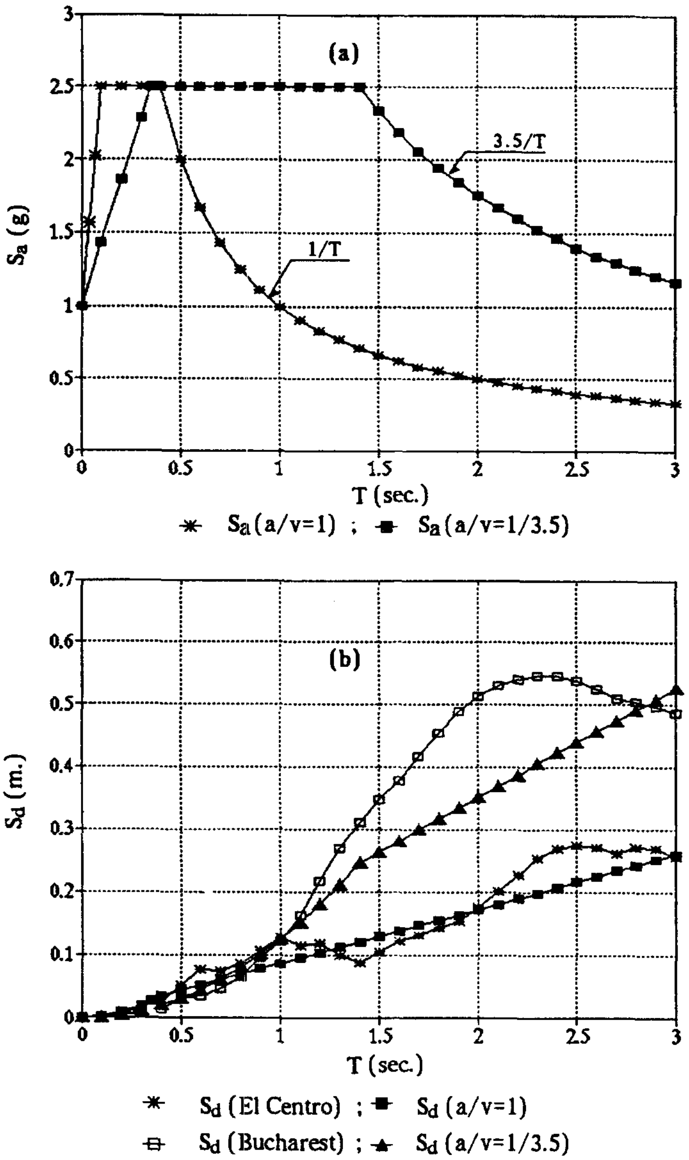


Figure 2. Design and response spectra: (a) UBC 1988 normalized acceleration spectrum and extrapolation. (b) El Centro, Bucharest, and their related UBC displacement spectra

The width of the gap between the two buildings depends on the seismic code used for their design, and on whether it has been kept free from debris. Most of the analyses assumed a gap width of 30 mm which is probably the minimum separation for buildings of more than two storeys, but results for wider gaps were also obtained. Period-dependent gaps were also considered using the well-known square-root-of-the-sum-of-squares (SRSS) formula

$$\text{gap} = \sqrt{\Delta_1^2 + \Delta_2^2} \quad (\geqslant 30\ \text{mm}) \tag{1}$$

in which $\Delta_i$ is the calculated (free motion) displacement of $i$th mass. The $\Delta_i$'s were based on the UBC 1988[15] 'Normalized Response Spectra Shapes' (Figure 3 therein) and on an extrapolation thereof for low $a/v$ earthquakes [Figure 2(a)]. Equation (1) leads to a narrower gap than the absolute sum of $\Delta_i$, but should be

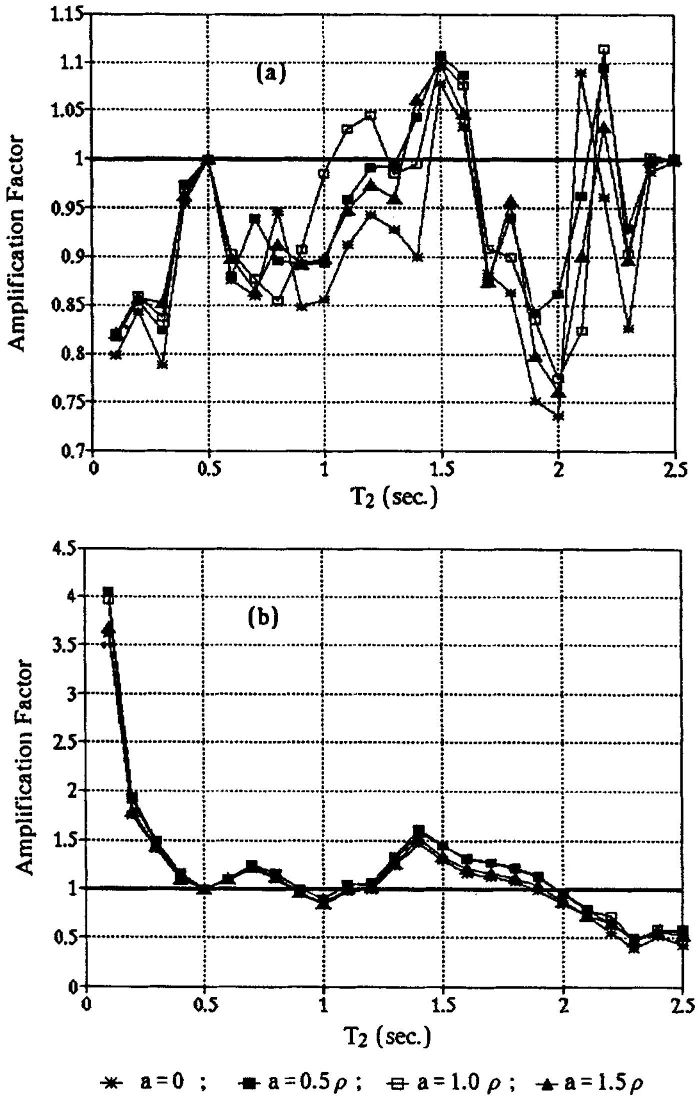


Figure 3. Symmetric alignment, El Centro record: Effect of 1st impact eccentricity on displacement amplification; $m_1 = m_2$; $T_1 = 0{\cdot}5$ s; $\Omega = 1{\cdot}0$; $\varepsilon = 0{\cdot}5$; gap = 30 mm. (a) Structure 1; (b) Structure 2

acceptable provided occasional hammering can be tolerated. The SRSS formula appeared in the Venezuelan code[16] already in the early 1980s. Recently a correction based on random vibration theory has been applied to it in order to reduce the gap when the natural periods of the two buildings are close.[17]

A coefficient of restitution $\varepsilon = 0{\cdot}5$ representing some loss of energy due to impact was assumed. This value is a conservative approximation to the experimental results reported elsewhere[12] for pounding of small ($1{\cdot}0 \times 1{\cdot}1 \times 0{\cdot}08$ m$^3$) reinforced concrete slabs. In addition, viscous damping (5 per cent of critical in each mode) was used, and the damping matrix $C$ was taken as proportional to the mass and stiffness matrices.

Finally, the excitation-time histories have to represent realistic distribution of input energy content. For this reason two records were used: El Centro 1940 with $a/v \approx 1{\cdot}0$ ($a$ = peak ground acceleration in units of $g$, and $v$ = peak ground velocity in m/s) with much energy in the low period range, and Bucharest 1977 ($a/v \approx 0{\cdot}27$), with energy in the higher range. The displacement spectra $S_d$ (5 per cent damping) for these two records are shown in Figure 2, together with the derived UBC spectra.

## ANALYSIS

The usual assumptions regarding the properties of the two models have been made, namely the floor is rigid in its own plane, the mass $m$ is uniformly distributed with its centre CM at the geometric centre of the slab, the behaviour is linear elastic and no P-delta effects are considered.

The equations of motion for each of the two slabs about their respective mass centres are given by (Figure 1)

$$m_i\begin{bmatrix}1 & 0\\ 0 & \rho^2\end{bmatrix}\begin{Bmatrix}\ddot{u}_i\\ \ddot{\theta}_i\end{Bmatrix} + [C]\begin{Bmatrix}\dot{u}_i\\ \dot{\theta}_i\end{Bmatrix} + \begin{bmatrix}k_{yi} & 0\\ 0 & k_{\theta i}\end{bmatrix}\begin{Bmatrix}u_i\\ \theta_i\end{Bmatrix} = -m_i\begin{Bmatrix}\ddot{u}_g\\ 0\end{Bmatrix}; \quad i = 1,2 \tag{2}$$

in which $u$ is the relative lateral displacement, $\theta$ is the rotation about the vertical axis, $\ddot{u}_g$ is the ground acceleration, $k_y$ is the lateral stiffness, and $k_\theta$ is the rotational stiffness with respect to CM (= CR — rigidity

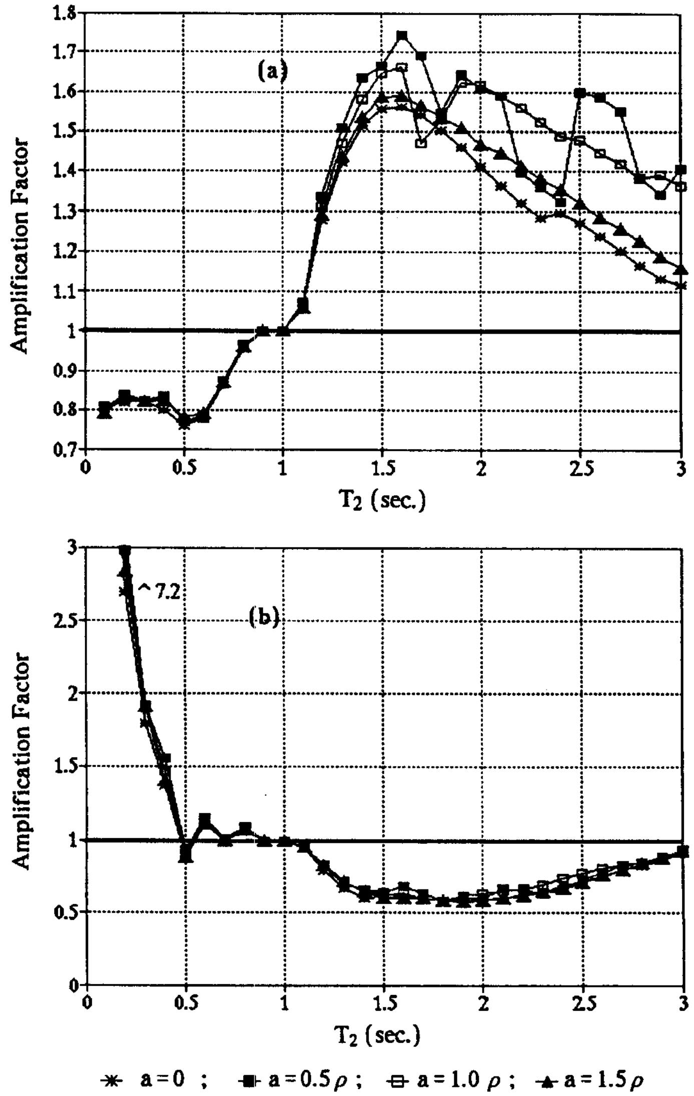


Figure 4. Symmetric alignment, Bucharest record: Effect of 1st impact eccentricity on displacement amplification; $m_1 = m_2$; $T_1 = 1{\cdot}0$ s; $\Omega = 1{\cdot}0$; $\varepsilon = 0{\cdot}5$; gap = 30 mm. (a) Structure 1; (b) Structure 2

centre). The equations are linear with time-dependent initial conditions. These were solved in incremental form using the Newmark $\beta$-method with $\beta = \frac{1}{4}$. Contact is made when the gap at any location along the interface is equal to or smaller than zero, and overlapping (OL) is controlled by means of a displacement constraint MOL (= gap/1000, in this study). When the constraint is violated the analysis is repeated using a smaller time step, and once $0 < \text{OL} \leqslant \text{MOL}$ the equations of rigid body impact are assumed to apply. The following relations between the pre-impact and post-impact linear and angular velocities hold:[14]

$$\begin{aligned} v_{1,a} &= v_{1,b} + \bar{m}(1+\varepsilon)q\,v_r m_1 \\ v_{2,a} &= v_{2,b} - \bar{m}(1+\varepsilon)q\,v_r m_2 \\ \omega_{1,a} &= \omega_{1,b} + \bar{m}(1+\varepsilon)q\,a_1 v_r/I_{m1} \\ \omega_{2,a} &= \omega_{2,b} + \bar{m}(1+\varepsilon)q\,a_2 v_r/I_{m2} \end{aligned} \tag{3}$$

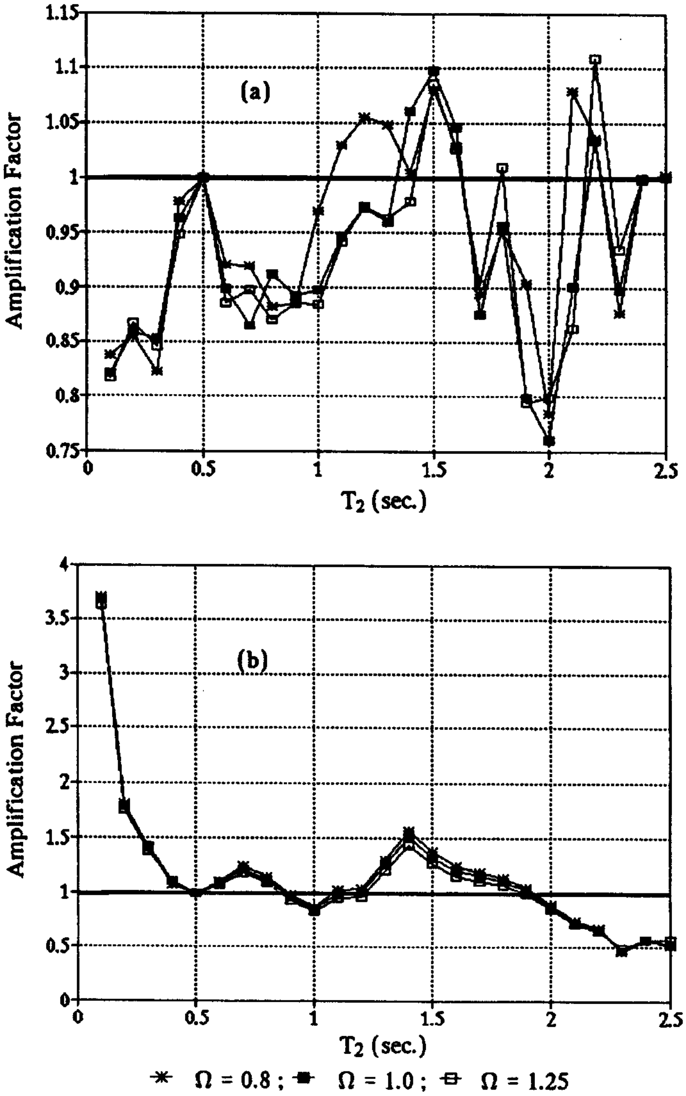


Figure 5. Symmetric alignment, El Centro record: Effect of lateral-to-torsional frequency ratio on displacement amplification; first impact at corner ($a = 1{\cdot}5\rho$); $m_1 = m_2$; $T_1 = 0{\cdot}5$ s; $\Omega = 0{\cdot}8$, $1{\cdot}0$, $1{\cdot}25$; $\varepsilon = 0{\cdot}5$; gap = 30 mm. (a) Structure 1; (b) Structure 2

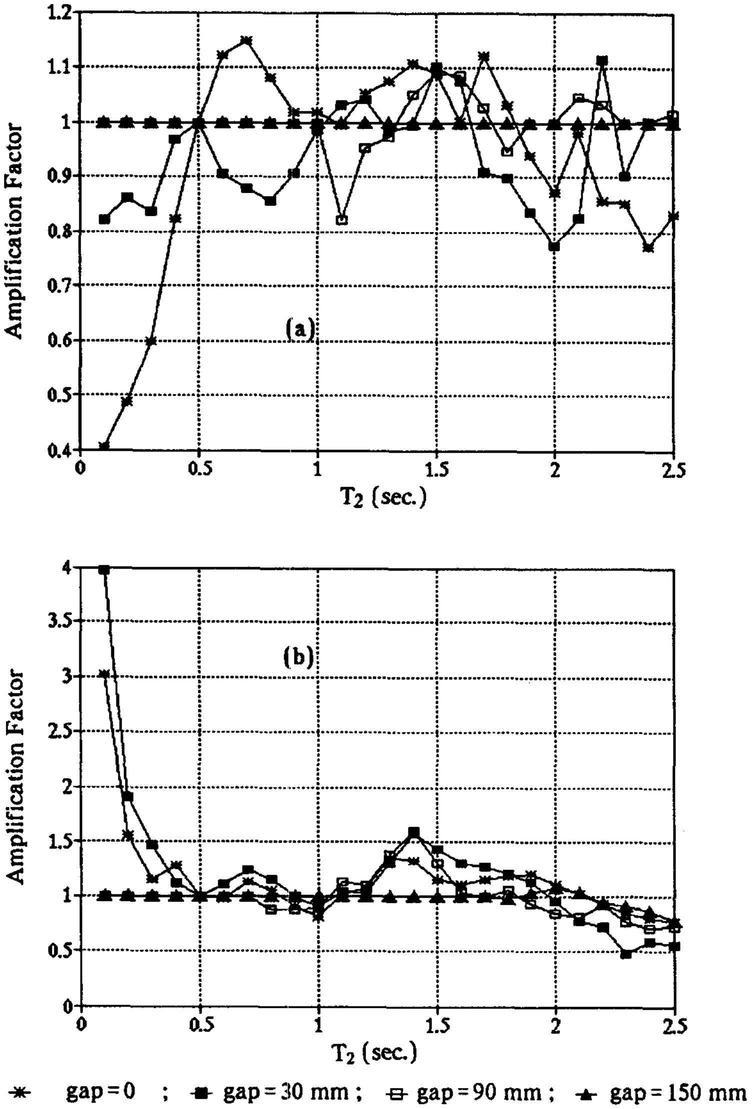


Figure 6. Symmetric alignment, El Centro record: Effect of gap size on displacement amplification; $m_1 = m_2$; $T_1 = 0{\cdot}5$ s; $\Omega = 1{\cdot}0$; $\varepsilon = 0{\cdot}5$; gap = 0, 30, 90, 150 mm; first impact at $a = 1{\cdot}0\rho$. (a) Structure 1; (b) Structure 2

in which $v_i$ is the normal velocity of slab $i$ ($i = 1, 2$), $\omega_i$ is the angular velocity, $a_i$ is the $x$ direction distance from mass centre to point of impact (Figure 1), $I_{mi}$ is the moment of inertia of slab with respect to its CM, $\varepsilon$ is the coefficient of restitution ($\varepsilon = 1{\cdot}0$ — elastic impact, $\varepsilon = 0$ — plastic impact),

$$\bar{m} = \frac{m_1 m_2}{m_1 + m_2}; \qquad q = 1 + \frac{\bar{m}a_1^2}{I_{m1}} + \frac{\bar{m}a_2^2}{I_{m2}}; \qquad v_r = (v_{2,\mathrm{b}} - a_2\omega_{2,\mathrm{b}}) - (v_{1,\mathrm{b}} - a_1\omega_{1,\mathrm{b}})$$

The indices b and a denote respectively before and after impact quantities. The values $v_{i,\mathrm{a}}$ $(= \dot{u}_{i,\mathrm{a}})$ and $\omega_{i,\mathrm{a}}$ $(= \dot{\theta}_{i,\mathrm{a}})$, with $u_i$ and $\theta_i$ are the initial conditions for the subsequent round of step-by-step solutions of equation (2).

The effect of the relative tangential velocity at the interface of the two slabs on eccentric impact has been eliminated in this study by assuming frictionless contact. This not very realistic assumption was made only to

simplify the analysis. However, recent preliminary analyses[12] have shown that friction does not appreciably affect the results presented herein, but for conclusive results further study is needed.

## RESULTS

Most of the results are presented as response amplification spectra. These are ratios of the peak displacements at the *extremity* of the floor slab ($Y_p$) to the respective peak displacements when the masses are free to vibrate under the same ground motion ($Y_0$). This ratio is called the amplification factor. Therefore, to obtain the absolute displacement, $Y_p/Y_0$ should be multiplied by the applicable spectral displacement $S_d$ given in Figure 2 for the El Centro and Bucharest records. In the figures that follow, the spectra are given for each of the two structures as a function of the natural period of Structure 2 ($= T_2$).

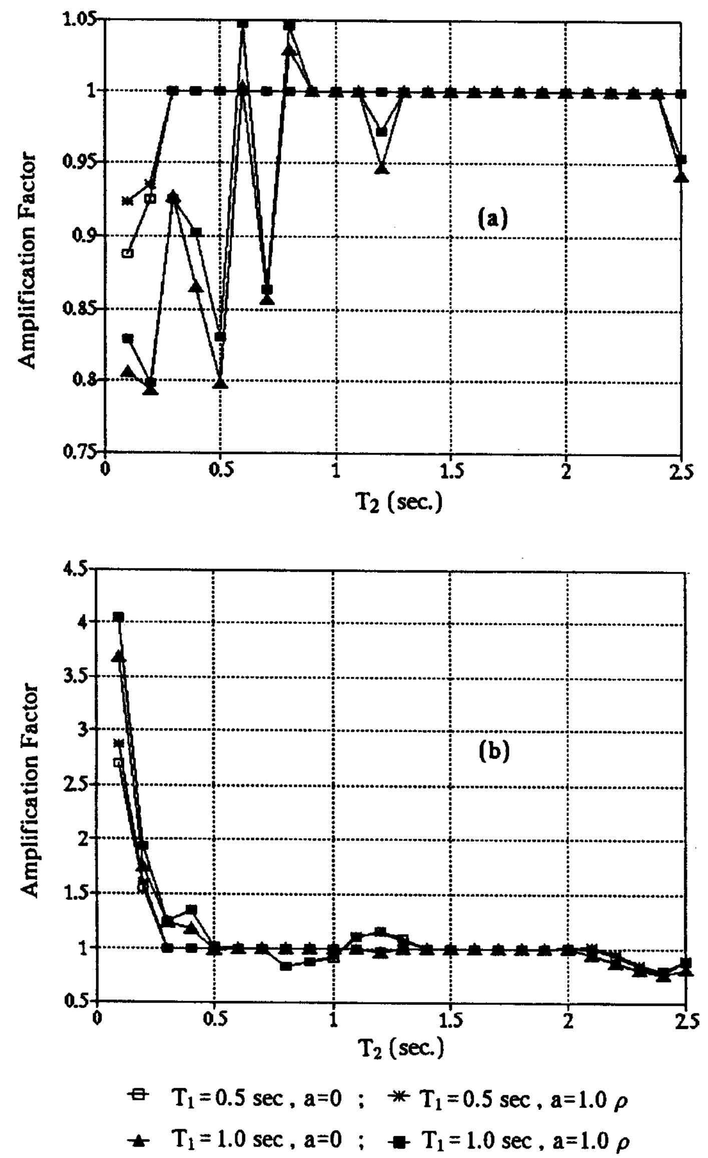


Figure 7. Symmetric alignment, El Centro record: Effect of variable gap [equation (1)] on displacement amplification; $m_1 = m_2$; $T_1 = 0{\cdot}5$, $1{\cdot}0$ s; $\Omega = 1{\cdot}0$; $\varepsilon = 0{\cdot}5$; first impact at $a = 0$, $1{\cdot}0\rho$. (a) Structure 1; (b) Structure 2

The period ranges $0 \leqslant T_2 \leqslant 2{\cdot}5$ s for El Centro and $0 < T_2 \leqslant 3{\cdot}0$ s for Bucharest, which are relatively wide for buildings of equal height, have been chosen, mainly to highlight period dependent trends. Yet they are not necessarily unrealistic since the stiffness ratio of two low-rise buildings of similar mass may be very large (shear walls vs. frames).

Results for the symmetric configuration [Figure 1(a)] are presented first. The system consists of two adjacent symmetric structures of identical configuration, but with different natural periods that make first contact at any one of four predetermined collision points ($a = 0, 0{\cdot}5\rho, 1{\cdot}0\rho, 1{\cdot}5\rho$). The results for gap = 30 mm, $m_1 = m_2$ and $\Omega = 1{\cdot}0$ are shown in Figures 3 and 4 for the El Centro and Bucharest records respectively with $T_1 = 0{\cdot}5$ s in Figure 3 and 1·0 s in Figure 4. It can be seen that eccentricity at first impact ($a \neq 0$) increases the response of Structure 1, although a larger eccentricity does not necessarily lead to larger amplification. It is also seen that the large displacement amplification of Structure 2 in the

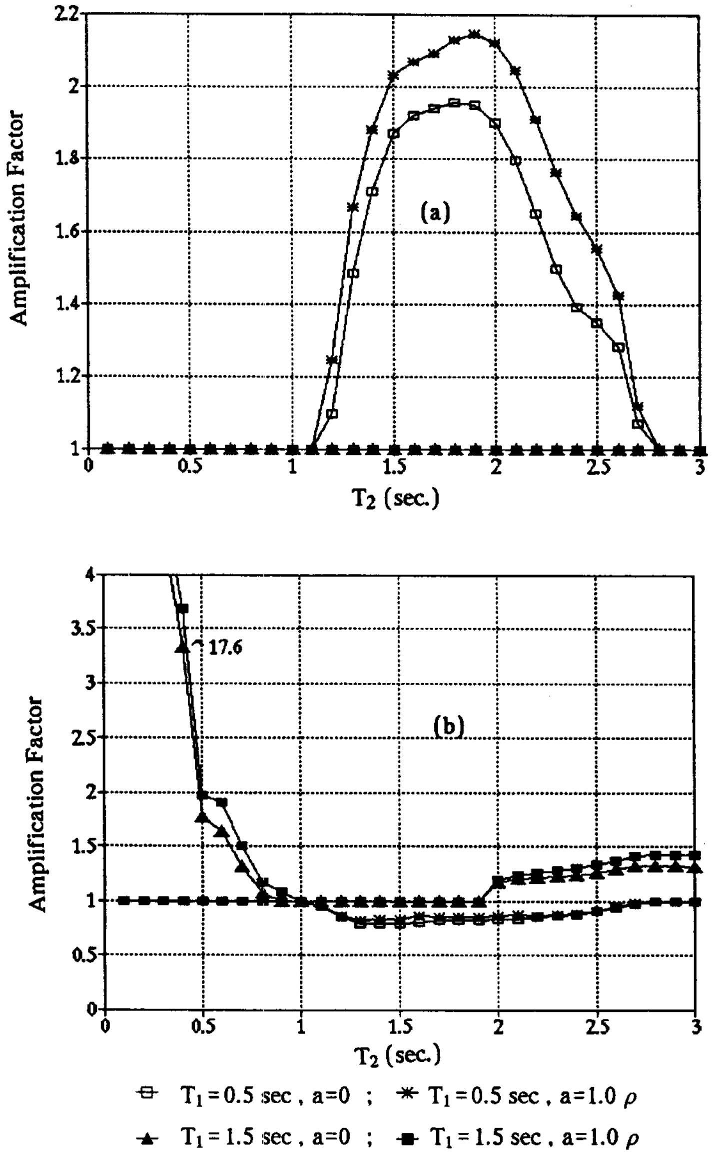


Figure 8. Symmetric alignment, Bucharest record: Effect of variable gap [equation (1)] on displacement amplification; $m_1 = m_2$; $T_1 = 0{\cdot}5, 1{\cdot}5$ s; $\Omega = 1{\cdot}0$; $\varepsilon = 0{\cdot}5$; first impact at $a = 0, 1{\cdot}0\rho$. (a) Structure 1; (b) Structure 2

very low period range is not a result of eccentricity, as already noted[12,13] although the latter adds to it to some extent.

The effect of the rotational to lateral frequency ratio $\Omega$ on the amplification of displacement is shown in Figure 5 for initial impact at $1{\cdot}5\rho$ (the corner). It is seen that the effect is not strong, although as expected, some reduction in amplification with increasing $\Omega$ can be observed for both structures. Results for Bucharest predict a somewhat larger amplification in the very high period range of Structure 2 when $T_1 = 1{\cdot}5$ s (not shown).

Figure 6 shows the effect of gap width on the amplification. It can be seen that pounding is practically eliminated only when the gap is not significantly smaller than that required for free motion. However, when the gap is smaller the amplification does not fall with increasing gap width—in fact it is quite erratic. Thus in this respect the results appear to be similar to those of symmetric systems.[12,13]

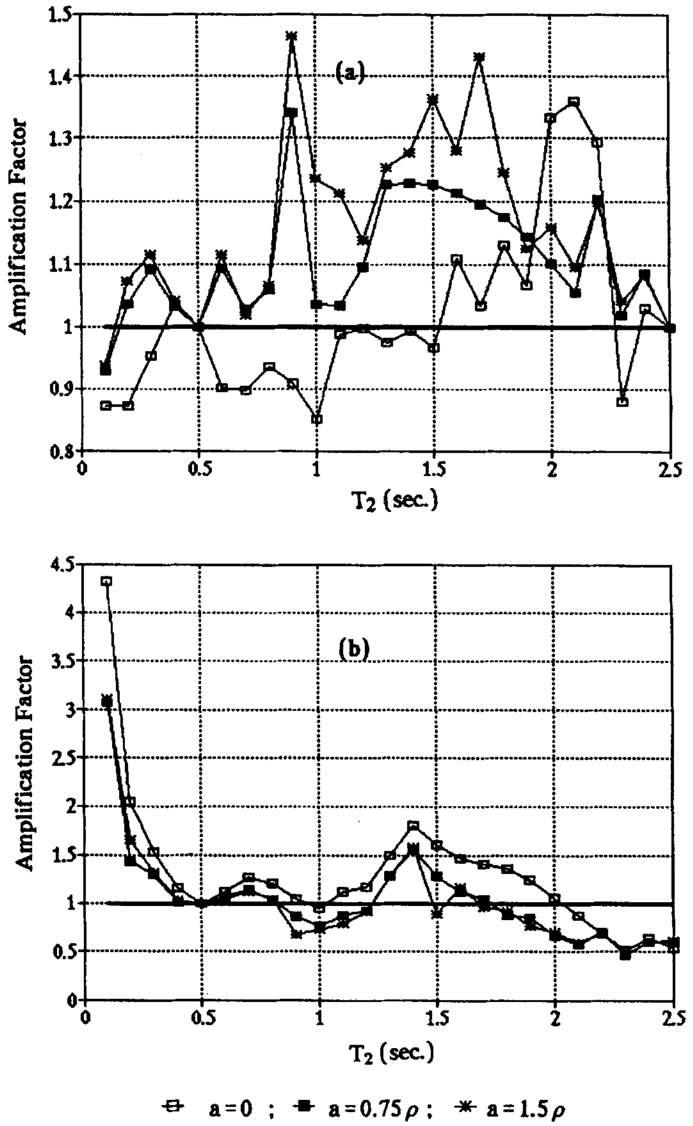


Figure 9. Asymmetric alignment [Figure 1(b)], El Centro record: Effect of 1st impact eccentricity on displacement amplification; $m_1 = m_2$; $T_1 = 0{\cdot}5$ s; $\Omega = 1{\cdot}0$; $\varepsilon = 0{\cdot}5$; gap = 30 mm. (a) Structure 1; (b) Structure 2

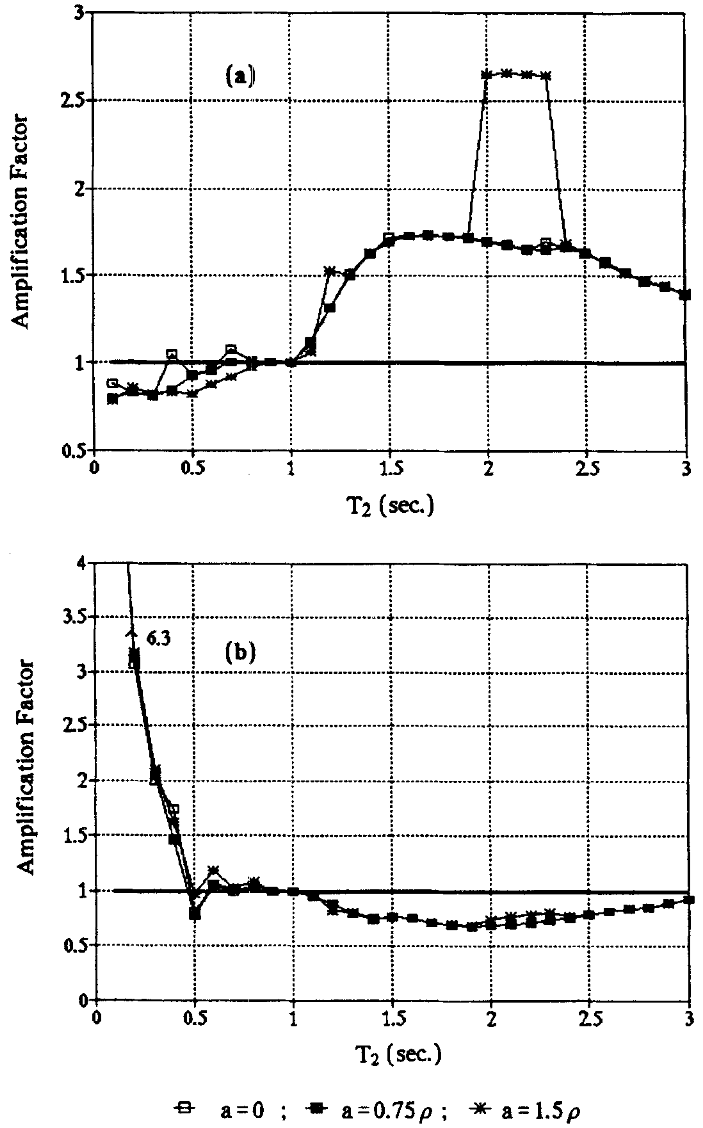


Figure 10. Asymmetric alignment [Figure 1(b)], Bucharest record: Effect of 1st impact eccentricity on displacement amplification; $m_1 = m_2$; $T_1 = 1{\cdot}0$ s; $\Omega = 1{\cdot}0$; $\varepsilon = 0{\cdot}5$; gap = 30 mm. (a) Structure 1; (b) Structure 2

The results for the gap width evaluated by equation (1) are given in Figures 7 and 8. It is seen that pounding has not been eliminated in the very low period range of Structure 2 for the El Centro record, and in the medium to high range of Structure 1 for Bucharest. Note also that the effects of asymmetry are relatively small. Analyses were also carried out for a 20 mm protrusion at $a = 1{\cdot}0\rho$, modelling the presence of hard debris. As expected, its presence augmented the response moderately (circa 10 per cent, not shown). It was also found that increasing the gap width to the absolute sum of the design displacements, as required by most codes, lowered the amplification only marginally (not shown).

Typical results for the asymmetric configuration shown in Figure 1(b) with a constant gap are given in Figures 9–11. The amplification levels of Structure 1 are higher than those of the configuration in Figure 1(a) considered earlier, where the two slabs are symmetrically aligned and have full-length interface. Note the larger response when the first impact occurs at the mid point of Structure 1 ($a = 0$). As can be seen from

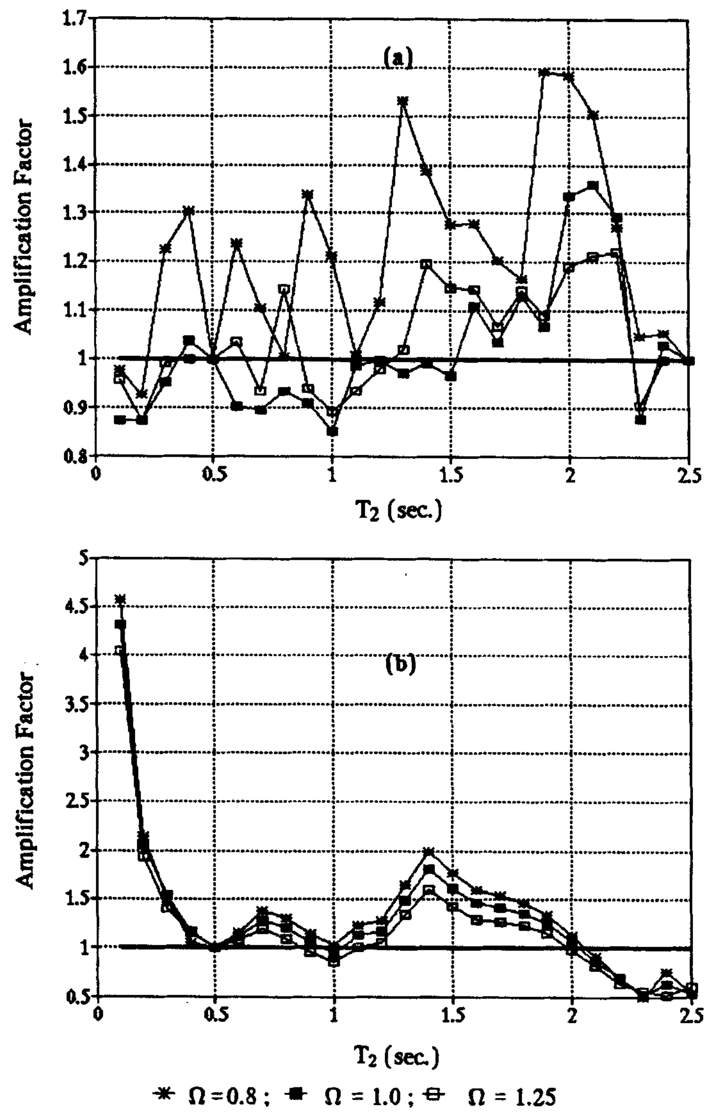


Figure 11. Asymmetric alignment [Figure 1(b)], El Centro record: Effect of lateral to torsional frequency ratio on displacement amplification, $m_1 = m_2$; $T_1 = 0{\cdot}5$ s; $\Omega = 0{\cdot}8, 1{\cdot}0, 1{\cdot}25$; $\varepsilon = 0{\cdot}5$; gap = 30 mm; first impact at $a = 0$ (Structure 1). (a) Structure 1; (b) Structure 2

Figure 11 the moderating effect of larger $\Omega$ appears to be somewhat larger than in symmetrically aligned systems.

The effect of the variable gap [equation (1)] on the response of asymmetrically aligned systems has also been studied. The results (Figures 12 and 13) show larger response for Structure 1 than for symmetrically aligned systems.

## CONCLUSIONS

On the whole, the effect of the parameters varied in this study is not strongly manifested in the response spectra. This is due to the nature of the pounding phenomenon, which is sensitive to small changes in the motion, combined with the random ground excitation. Yet, several conclusions can be drawn. Eccentricity at first impact results in larger amplification compared with symmetric impact, but in symmetrically aligned

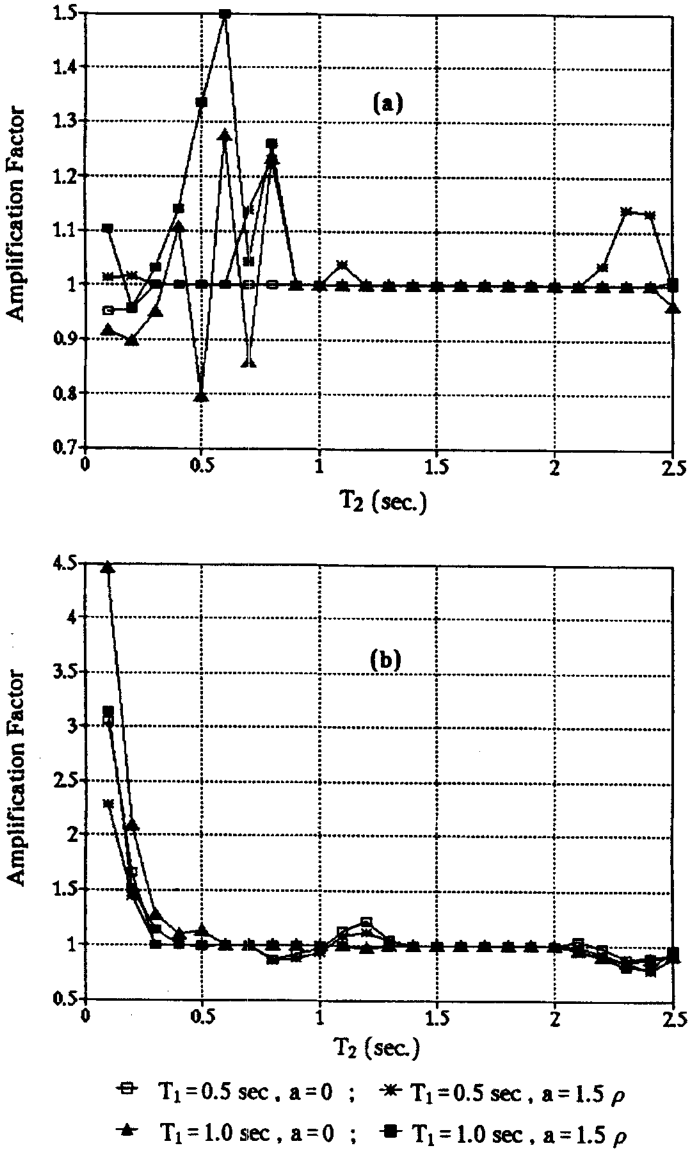


Figure 12. Asymmetric alignment, El Centro: Effect of variable gap [equation (1)] on displacement amplification; $m_1 = m_2$; $T_1 = 0{\cdot}5$, $1{\cdot}0$ s; $\Omega = 1$; $\varepsilon = 0{\cdot}5$; first impact at $a = 0$, $1{\cdot}5\rho$ (Structure 1). (a) Structure 1; (b) Structure 2

systems, the amplification does not increase with eccentricity due to the mutual rotational constraint of the two slabs. As can be expected, the amplification falls to some extent with increasing torsional-to-lateral frequency ratio of the two systems, and this trend is more pronounced for asymmetrically aligned systems. On the whole the amplification of the latter systems is somewhat higher than that of symmetrically aligned ones.

A design spectrum based SRSS formula for combining the predicted two displacements to obtain pounding-free separation has been tested. This formula is quite effective provided the design spectrum is consistent with the expected ground motion at the site, i.e. the acceleration design spectrum for Bucharest requires an even wider plateau than provided in this study in order to envelope the spectral displacements when $T > 1{\cdot}0$ s. However, particularly in the very low period range, the prescribed gap for El Centro is not wide enough, and large amplifications result already in symmetric impact and which the eccentricity of the

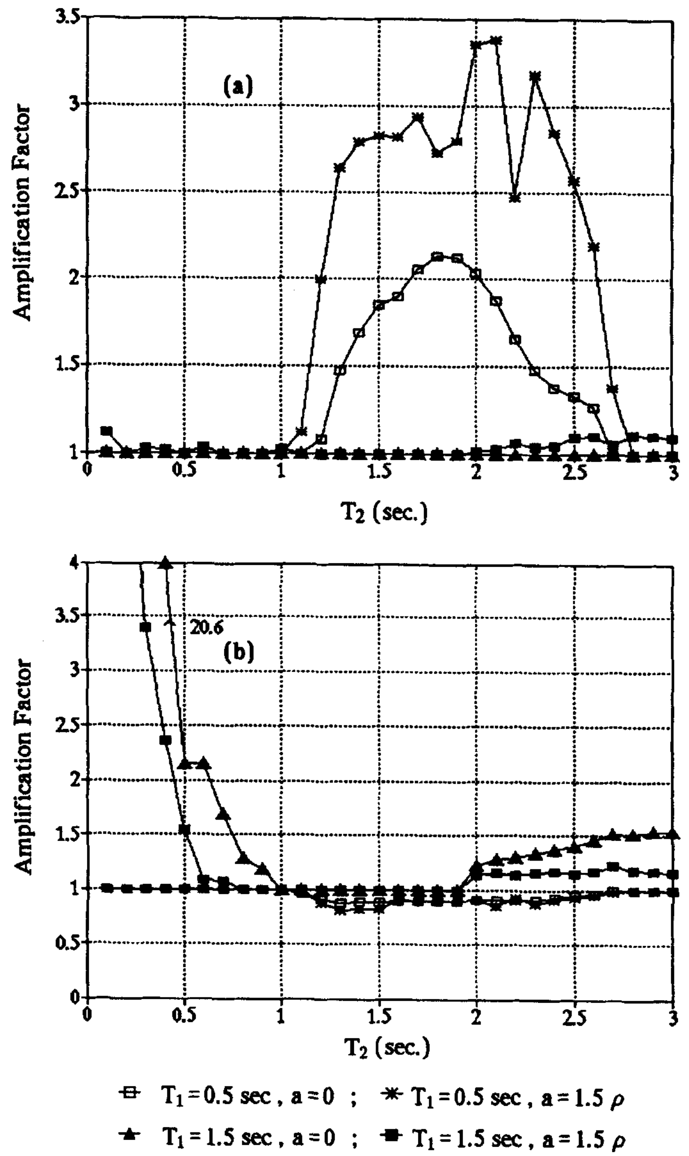


Figure 13. Asymmetric alignment, Bucharest record: Effect of variable gap [equation (1)], on displacement amplification; $m_1 = m_2$; $T_1 = 0{\cdot}5, 1{\cdot}5$ s; $\Omega = 1$; $\varepsilon = 0{\cdot}5$; first impact at $a = 0, 1{\cdot}5\rho$ (Structure 1). (a) Structure 1; (b) Structure 2

first impact magnifies. This behaviour presents a case for increasing the minimum gap width prescribed in seismic codes. On the other hand, it should not be overlooked that the large amplifications occur when the period ratios of the two structures are also large. For two buildings of equal height such ratios represent extreme situations, and in the more common case there will be a difference in height resulting in appreciably smaller separation demand, particularly for flexural-type resisting systems. Moreover, many structures are designed to yield under severe ground motion and therefore only limited force amplification should be expected. For these structures it is possible to consider reduced gaps provided the increased ductility demand can be provided. These matters are discussed at some length in a separate study.

Several practical aspects of the problem have not been considered in the present study: pounding between asymmetric buildings, which covers as a particular case accidental torsion in symmetric systems, which when

considered will lead to larger gap widths, and between buildings of different heights. Whereas the former is a simple extension of the present study the latter problem requires multi-degree-of-freedom modelling. These problems are also being addressed by the authors.

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